Forces

"Our business is with the causes of sensible effects"

I. Newton

OBJECTIVES

To see some situations where forces produce accelerations.

THEORY

So far we have concentrated on kinematics, the description of motion. For this exercise we will examine some of the causes of motion, a subject called dynamics.

Newtonian dynamics centers on forces, which produce accelerations. Forces, such as gravity, rubber bands or friction, are part of the environment of the object we are studying. When one or more forces act on a mass it accelerates according to the celebrated Newtonian law

$$\mathbf{F} = m\mathbf{a} \tag{1}$$

There are several aspects of this law that can be studied. A force of constant magnitude evidently produces a constant acceleration. Also, for constant force the acceleration should be inversely proportional to the mass of the accelerated object. Perhaps odder, it seems that the acceleration in some chosen direction is proportional to the vector component of the force in that direction, independent of other components. All of these effects can be observed without instruments, as well as being quantitatively measurable.

EXPERIMENTAL PROCEDURE

The object whose motion you will study is a heavy cart which is free to roll in a straight line across the table. Forces will be applied by your hands, by springs and, inevitably, by friction. Pushing or pulling the cart with your hands will help you directly experience the effect of the forces. Springs are useful for more quantitative exercises because the force they exert is constant if their length is constant. By pulling the cart across the table with a spring stretched to a chosen length we can find out if a constant force does indeed produce constant acceleration. If that works, we can get the average acceleration in other constant-force situations by finding the change in velocity over a known time interval. That procedure will let us investigate various aspects of Eq. 1 fairly quickly.

Before starting the measurements, there are a couple of precautions you need to take. Most important, the cart is heavy, about 15 kg (~ 33 lbs). *Do not let it fall off the table.* The bumpers will help confine the cart, but don't count on them to stop a fast-moving cart. Stop or at least slow the cart by hand before it hits the bumper.

Start your work by accelerating the cart by hand to get a feel, literally, for the effect of a force. There are several questions to examine qualitatively by experimentation and discuss in your report in the context of Eq. 1.

1. If you start moving the cart on your table at a modest velocity, how does it move when you stop pushing?

2. How does this compare to the motion of a more ordinary object, say a book, sliding across your table?

3. What accounts for the difference?

4. What is the difference in the motion of the cart when you push steadily on it with a constant force versus giving it a single quick shove?

5. What must you do to bring a moving cart to a smooth, gradual stop?

6. Suppose you exert two steady forces on the cart in opposite directions, one force with each hand. How does the cart behave when one force is larger than the other?

7. How about when the forces are of equal magnitude?

8. Would pushing the cart forward (parallel to the normal way that the cart would roll) with a constant force or pushing the cart sideways (perpendicular to the normal way that the cart would roll) with the same magnitude of force, cause the cart to move with the same speed? Why not?

Next you should use the video acquisition system to see if a constant force produced by a spring does indeed produce constant acceleration. Practice towing the cart with a spring and

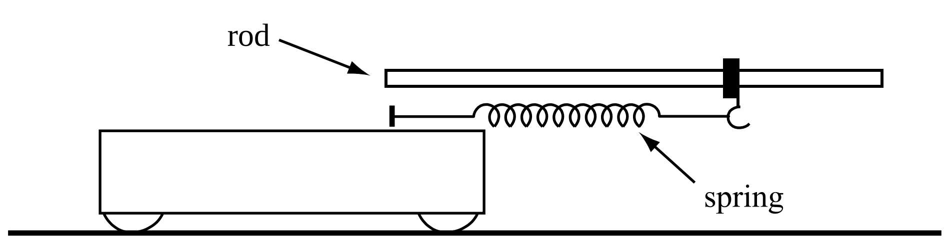


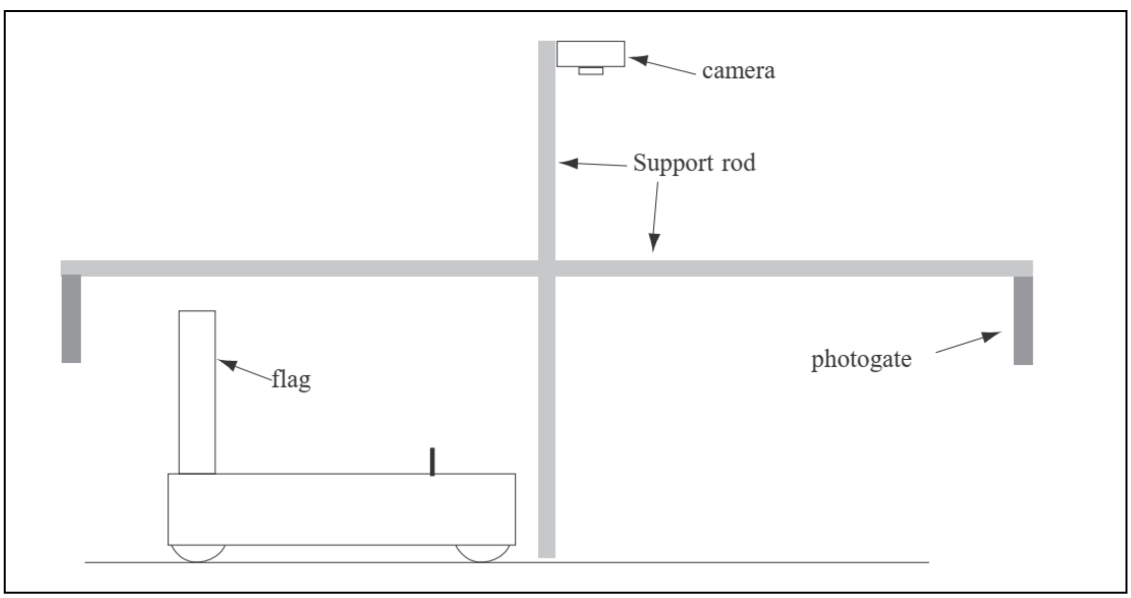
Fig. 1 Side view of cart being towed by spring. If the rod is moved to keep its end over the towing post on the cart, the length of the spring will be constant.

measuring rod, as suggested by Fig. 1, until the motion is smooth and reproducible. **The stretch length** of the spring should be kept **between 30 cm and 40 cm**. **When moving the cart, keep the end of the rod hovering directly above the towing post on the cart (the metal post on the cart where the spring is attached). The length of the spring must be held constant as the cart moves. This means you must walk backward while you tow the cart. While towing the cart, the rod must NOT touch any part of the cart including the towing post.** Please catch the cart *before* it hits the safety bumper to minimize the risk of damaging anything.

When the towing procedure works smoothly, capture a short movie of the accelerating cart. Start LoggerPro from the file **Graph.cmbl** on the computer desktop to configure it to capture the movie by going to Insert > Video Capture, and to obtain a graph of position vs time for the cart. (If asked by LoggerPro, please choose "Use file as is"). If the acceleration due to the force of the constant-length spring is constant, what relationship would you expect the position vs time plot of the cart to follow? Try to fit your position vs time data with the expected relationship and decide if the motion is adequately described by constant acceleration. Would a constant frictional force that might also be acting on the cart affect the functional relationship between the position vs time of the cart? Explain. What about a gravitational force along the direction of motion due to a tilted table top? Explain. **Quit LoggerPro and DO NOT save.**

Angular Dependence:

If you successfully demonstrated that the stretched spring produces constant acceleration, you can check the angular dependence implied by the **vector nature of Eq. 1** by applying a constant force to the cart at different angles. In this part of the lab, you will pull the cart at different angles using the spring. **In this part, you will determine the acceleration at a given time directly using the photogates. DO NOT capture a movie for each different angle.** The apparatus required is sketched in Fig. 2.



Set up the two U-shaped photogates so that the path of the cart runs under both. Attach the metal flag vertically to the magnet at the side of the cart (make sure the long sides of the metal flag sit as perpendicularly as possible to the cart) and adjust the height of the gates so that the metal flag goes through the photogates without hitting. **Plug the power adapter for the "Vernier Lab pro" box into a power outlet if you have not already done so. The "Vernier Lab pro" box is the rectangular green box with various wires attached.**

To collect data, start LoggerPro from the file **Forces.cmbl** on the computer desktop. This configures the data acquisition hardware and software. **If you DO NOT start LoggerPro from Forces.cmbl, you will NOT be able to collect the data correctly.** The file **Forces.cmbl** tells LoggerPro to connect with the Vernier Lab Pro interface, measures the times at which the flag enters and leaves the photogate. (It detects blocking of an infrared light beam that goes across the U-shape from an emitter to a sensor.) **These times are listed on the first column of the data table on the computer.** LoggerPro estimates the average speed at the gate position by the width of the flag Δx and dividing by the time that the gate is blocked, Δt

$$v = \frac{\Delta x}{\Delta t} \qquad (2)$$

You DO NOT need to measure Δx, the width of the metal flag is already written into Forces.cmbl. However, if the long sides of the metal flag do not sit as perpendicularly as possible to your cart, then the Δx used by LoggerPro to calculate the average speed will not be correct. If the metal flag, and therefore the time interval, is short, then $\Delta x/\Delta t$ will be a reasonable approximation to the instantaneous speed at the position of the gate. The software does these calculations and provides the times and velocities at each gate. On the computer data table, when "Gate state 1" and Gate state 2" is 1, that corresponds to when the metal flag first blocks the corresponding photogate, and when "Gate state 1" and Gate state 2" is 0, that corresponds to when the metal flag first unblocks the corresponding photogate.

Before collecting data, adjust the stretch of the spring so that the force is large enough to move the cart when applied at a fairly big angle, but not so large that you cannot keep up with the motion at small angles. **It is recommended that you use a stretch length between 30 cm and 40 cm.** You should make sure the stretch length you set is long enough that there will be enough force on the cart to move it across the table when you are towing it at the largest angle that you plan on using. **<u>Once you decide on a stretch length, then the stretch length CANNOT be changed for the remainder of this lab.</u>**

Click on , wait a few seconds for the computer to respond, tow the cart through the photogates at a constant acceleration and then click  once the metal flag clear both photogates. As you move the cart through the two photogates, you should see numbers populating the table on the computer with columns labeled as: time, GateState 1, Velocity 1, GateSate 2, and Velocity 2. **<u>On the data table on your lab report, "t_1" corresponds to the time when "GateState 1" is equal to 0, and "t_2" corresponds to the time when "GateState 2" is equal to 0. "v_1" corresponds to the velocity at "t_1", and "v_2" corresponds to the velocity at "t_2".</u>** On the data table of your lab report, you will have to manually calculate cos (θ) and the average acceleration. **<u>The average acceleration is calculated using the two average velocities v_1 and v_2, and the time interval between them.</u>** Do this for the same force (same stretch length) applied at various angles θ relative to the direction that the cart is moving. You should take data for at least five well-spaced out angles.

A quantitative analysis of the data is straightforward, assuming the validity of Eq. 1. For the component in the direction of motion

$$a = \frac{F}{m}\cos\theta - \frac{f}{m} \tag{3}$$

,where F is the force from the spring and f is a frictional force. This suggests that a plot of the measured acceleration vs $\cos\theta$ should be a straight line. **<u>The measured acceleration must be the value on the vertical axis of your plot.</u>** <u>You can use the file</u> **<u>Graph.cmbl</u>** on the computer desktop <u>to plot the measured acceleration vs $\cos\theta$</u> (If you start *LoggerPro* from the taskbar, it will be slow and somewhat confusing. If asked by LoggerPro, please choose "Use file as is"). Is your measured acceleration linearly related to $\boldsymbol{\cos\theta}$? You will need to know the uncertainty in the calculated slope and y-intercept of your linear fit. If you do not see those values in the result box from your linear fit on your plot, you will need to double click on the result box, and click on the box next to "Show Uncertainty" and then click "OK".

What are the magnitudes of the spring force and the frictional force with uncertainty estimated using the 2N+1 method?

It is a bit harder to demonstrate the mass dependence because the frictional force may also change with mass. However, if you repeat the angular dependence measurements **with the same spring extension** and **the extra weight** on the cart you can find the new frictional force. The spring force should, of course, come out the same, providing a check on our deduction. You should take data for at least four well-spaced out angles. **Please unplug the power adapter of the "Vernier Lab pro" box from the power outlet and remove the extra weight from the cart once you finished collecting data.**